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RHESSI e^+-e^- ANNIHILATION RADIATION OBSERVATIONS: IMPLICATIONS FOR CONDITIONS IN THE FLARING SOLAR CHROMOSPHERE

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ABSTRACT

RHESSI has measured the positron-electron annihilation line and continuum in three solar flares: 2002 July 23, 2003 October 28, and 2003 November 2. The 511 keV line was broad (∼4–8 keV) in all three flares, consistent with annihilations in an ambient ionized medium at temperatures above 10^5 K. The measured continuum from positronium and from Compton scattering was unobservable, with the exception of the first 4 minutes of the October 28 flare observation; this indicates that the density at which most annihilations occurred was greater than $\sim 10^{14}$ H cm^{-3}. The width of the line narrowed in 2 minutes to ∼1 keV late in the October 28 flare, consistent with annihilation in ionized H $< 10^4$ K and $\geq 10^{15}$ cm^{-3}. There is evidence for a similar decrease in line width late in the November 2 flare. These observations suggest a highly dynamic flaring atmosphere at chromospheric densities that can reach transition-region temperatures, then cool to less than 10^4 K in minutes while remaining highly ionized. Although the energy contained in high-energy accelerated particles may have been enough to heat the plasma, the rate of deposition is not correlated with the temperature determined by the 511 keV line width, and this raises questions about the energy source.

Subject headings: Sun: chromosphere — Sun: flares — Sun: particle emission — Sun: X-rays, gamma rays

1. INTRODUCTION

Flare-accelerated ions interact with the solar atmosphere to produce radioactive nuclei (Kozlovsky et al. 1987) and pions (Murphy et al. 1987) that decay, yielding positrons. Positrons slow down by interactions with the ambient medium prior to directly annihilating with electrons or forming the hydrogen-like positronium atom. Direct annihilation and annihilation from the singlet state of positronium give rise to two 511 keV photons, while annihilation from the triplet state yields three photons with varying energies below 511 keV. The number of photons observed in this continuum divided by the number of photons in the line is known as the $3\gamma/2\gamma$ ratio. The 511 keV line shape, $3\gamma/2\gamma$ ratio, and time profile of the annihilation radiation are dependent on the temperature, density, composition, and ionization state of the ambient medium in which the positrons slow down, form positronium, and annihilate (Crannell et al. 1976). In a mostly neutral atmosphere with a temperature below 10^4 K, the line is complex. It is composed of a narrow (∼1.5 keV FWHM) component from annihilation with bound electrons and positronium formed by thermal charge exchange, and a broader component (∼7.5 keV FWHM) from positronium formed by charge exchange in flight (e.g., Bussard et al. 1979). At densities greater than $\sim 10^{13}$ cm^{-3}, the 3γ continuum is reduced (and the line yield is correspondingly increased) as a result of collisions that cause transitions from the triplet to the singlet state and the breakup of the positronium. Positrons are therefore an excellent probe of the physical conditions of the solar atmosphere close to where flare-accelerated ions interact.

The *Reuven Ramaty High-Energy Solar Spectroscopic Imager* (*RHESSI*; Lin et al. 2002) made the first high-resolution spectral observation of the solar positron-electron annihilation line during the 2002 July 23 solar flare (Share et al. 2003a). The line had a Gaussian width of 8.1 ± 1.1 keV (FWHM), which could originate either from annihilations at high temperatures (~ 4–7×10^5 K) or by positronium formation via charge exchange in flight at temperatures near 6000 K in a quiet solar atmosphere. Below, we discuss *RHESSI* measurements of annihilation radiation from the 2003 October 28 and November 2 flares, which reveal a broadened (∼4–8 keV FWHM) 511 keV line early in the observations, changes in the annihilation continuum flux, and a rapid narrowing of the line to ∼1 keV later in the flares. These measurements provide information on the density, temperature, and ionization state of the flaring solar chromosphere.

2. OBSERVATIONS

The Sun erupted between 2003 October 28 and November 4 and produced the most intense series of flares ever observed in the X-ray band. *RHESSI* began observing the 2003 October 28 X17.2 flare (AR 0486; S 16°, E 08°) at ∼11:06 UT after exiting the South Atlantic Anomaly (SAA). It missed the peak of hard X-ray and γ-ray line emission observed by the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*), which began at ∼11:02 UT (Gros et al. 2004). *RHESSI* observed the 2003 November 2 *GOES* X8.3 flare (AR 0486; S 13°, W 56°) from its onset at 17:16 UT until 17:28 UT, when the satellite entered the SAA. In order to minimize dead time and pulse pile-up effects, we analyzed data from the rear electronically separated segments of eight *RHESSI* high-resolution detectors (Smith et al. 2002). As we have done in previous analyses (Share et al. 2003a), we estimated the γ-ray background during these flares using the average of spectral accumulations on the previous and subsequent days (±15 orbits), when the satellite passed over similar geographic locations. In studying the solar annihilation line, we also corrected for an ∼2.5 keV wide instrumental line at 511 keV from positrons produced when flare radiation above 1 MeV interacted in the imaging grids, front Ge segments, and passive spacecraft material above and around the detectors (Share et al. 2003a).

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14. ABSTRACT **RHESSI has measured the positron-electron annihilation line and continuum in three solar flares: 2002 July 23 2003 October 28, and 2003 November 2. The 511 keV line was broad (∼4?8 keV) in all three flares, consistent with annihilations in an ambient ionized medium at temperatures above 105 K. The measured continuum from positronium and from Compton scattering was unobservable, with the exception of the first 4 minutes of the October 28 flare observation; this indicates that the density at which most annihilations occurred was greater than ∼1014 H cm 3. The width of the line narrowed in 2 minutes to ∼1 keV late in the October 28 flare, consistent with annihilation in ionized K and H ! 104 ≥1015 cm 3. There is evidence for a similar decrease in line width late in the November 2 flare. These observations suggest a highly dynamic flaring atmosphere at chromospheric densities that can reach transition-region temperatures, then cool to less than 104 K in minutes while remaining highly ionized. Although the energy contained in high-energy accelerated particles may have been enough to heat the plasma, the rate of deposition is not correlated with the temperature determined by the 511 keV line width, and this raises questions about the energy source.**			
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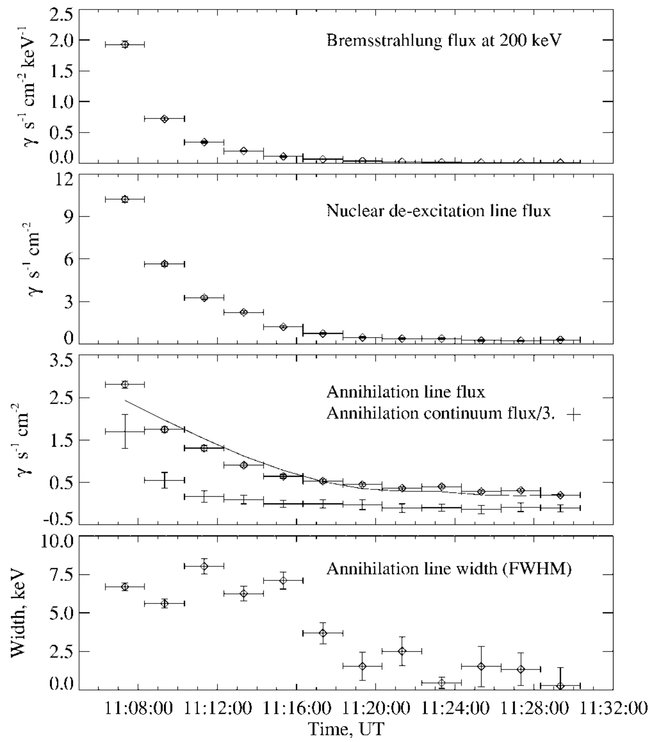

FIG. 1.—Time histories of the bremsstrahlung, total nuclear deexcitation line, and annihilation line and continuum fluxes, and the width of the annihilation line during the October 28 flare. The solid line in the third panel is the calculated 511 keV flux based on the nuclear-line flux (see text).

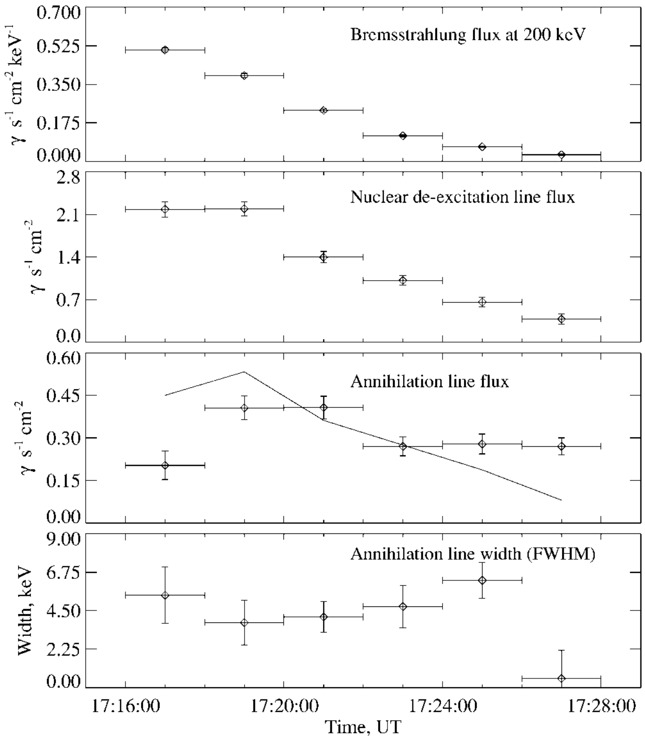

FIG. 2.—Time histories of the bremsstrahlung, total nuclear deexcitation line, and annihilation line fluxes, and the width of the annihilation line during the November 2 flare. The solid line in the third panel is the calculated 511 keV flux based on the nuclear-line flux (see text).

High-energy solar radiation consists of electron bremsstrahlung (modeled by a broken power law) and nuclear line and continuum radiation (e.g., Lin et al. 2003). We passed a solar photon spectrum with these components through the *RHESSI* instrument response function that calculates the photopeak intensity and shape, escape peaks, Compton continuum, and strength of the locally produced annihilation line (Smith et al. 2002). We then obtained the best fit to 200–8500 keV background-corrected count spectra in 2 minute intervals. In the top three panels of Figures 1 and 2, we plot the October 28 and November 2 time profiles of the fitted solar bremsstrahlung (at 200 keV), total nuclear deexcitation, and annihilation line fluxes. The values and statistical uncertainties (1 σ) were obtained by varying each parameter and mapping χ^2.

RHESSI observed rapidly decreasing fluxes when it commenced observations after the impulsive phase of the October 28 flare. The slower decay of the nuclear-line emission relative to the bremsstrahlung is consistent with delays observed in some other flares (Chupp 1990; Share & Murphy 2004). The annihilation line flux exhibited an even slower decay, because of the half-lives of the positron-emitting nuclei (Kozlovsky et al. 1987). The 511 keV line fluence observed by *RHESSI* was ~1100 γ cm^{-2}, a factor of 4 higher than the largest fluence measured by the *Solar Maximum Mission* (*SMM*; Vestrand et al. 1999). We used *RHESSI* and *INTEGRAL* (Gros et al. 2004) nuclear line fluxes to calculate the 511 keV time history based on the yields and lifetimes of positron emitters (Kozlovsky et al. 1987, 2004) and assumptions about the ambient and accelerated-particle abundances, spectra, and directionality (Ramaty et al. 1996; Share et al. 2003a). The solid line in the third panel is the calculated 511 keV flux that best fits both the amplitude and shape of the observed time history. Here we derived an index of ~2.8 for a power-law spectrum of accelerated particles, consistent with the ~3.4 index derived from a comparison of the total nuclear and 2.223 MeV neutron-capture time histories. Such a hard accelerated-particle spectrum, if extended up to hundreds of MeV, would produce π^+ mesons that decay with the emission of positrons, which could account for ~50% of the annihilation line flux. The Solar Neutron and Gamma Ray Spectrometer experiment (SONG) on *CORONAS-F* detected γ-rays above 60 MeV (Panasyuk et al. 2004), indicating the related production of π^0 mesons early in the flare.

RHESSI observed the onset of the November 2 flare, which rose rapidly and then decayed. This is reflected in the bremsstrahlung flux at 200 keV (Fig. 2). The nuclear-line emission once again exhibited a delay relative to the bremsstrahlung, and the annihilation line exhibited a further delay. The solid curve in Figure 2 shows our calculation of the annihilation-line flux described above. The best-fitting amplitude and shape again requires a hard accelerated-particle spectrum with a power-law index of ~2.9 (confirmed by other line measurements). There is a significant difference between the shapes of the calculated and observed time histories, which can be explained by extended π-meson production.

We also measured the Gaussian widths (FWHM) of the annihilation line as a function of time for the two flares, and obtained errors by mapping χ^2 (plotted in the bottom panels of Figs. 1 and 2). The October 28 line widths vary between ~5 and 8 keV on 2 minute timescales (with a 3×10^{-4} probability of being constant) during the first 10 minutes. The weighted mean of the widths was 6.5 ± 0.2 keV FWHM. This is narrower than the 8.1 ± 1.1 keV width measured during the 2002 July 23 flare (Share et al. 2003a). Significantly, there is no correlation between the line width and the continuum and line

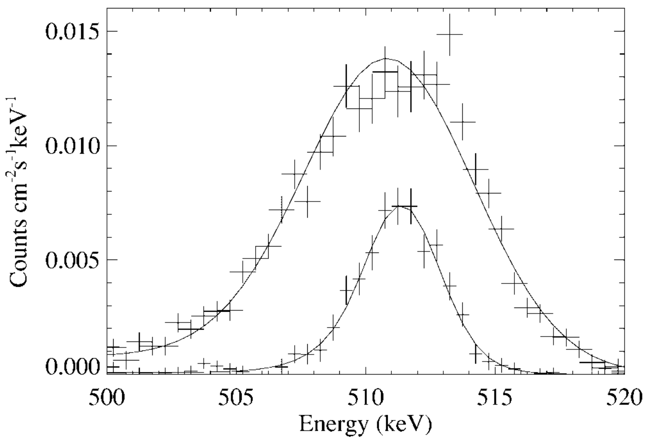

FIG. 3.—Count spectra of the solar 511 keV annihilation line (instrumentally broadened) derived by subtracting bremsstrahlung and nuclear contributions during the October 28 flare when the solar line was broad (11:06–11:16 UT) and narrow (11:18–11:30 UT). The solid curve is the best-fitting model that includes a Gaussian line and positronium continuum.

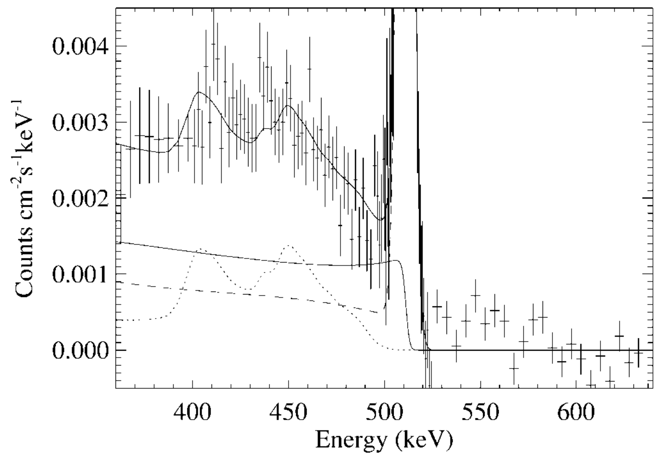

FIG. 4.—Expanded plot of a fit to the background-subtracted count spectrum from 11:06–11:10 UT on October 28 after removing bremsstrahlung and nuclear line contributions. Individual components are plotted separately and include the fit to the α-^{4}He line complex (*dotted line*), fit to the solar annihilation line (*dashed line*), and fit to the 3 γ positronium continuum (*solid line*; Compton scattering of the 511 keV line under 5–7 g cm^{-2} of H produces a similar continuum; see text). Excess counts >520 keV are from pulse pile-up.

fluxes, suggesting that the width is not directly related to the impact of relativistic electrons and ions. Beginning at 11:16 UT, the line narrowed strikingly; the mean width from 11:18 to 11:30 UT was 0.65 $\pm$ 0.65 keV. Nothing unusual was observed in the time histories of the bremsstrahlung, nuclear, and annihilation line fluxes when the line narrowed. The annihilation line was also broad during the first 10 minutes of the November 2 flare, with no significant evidence for variability or correlation with the bremsstrahlung and line fluxes. The mean width was 4.8 $\pm$ 0.5 keV FWHM, which is narrower than that observed on October 28. However, between 17:26 and 17:28 UT, the width decreased to 0.5 $\pm$ 1.6 keV, a value that is close to 3 σ below the mean width measured earlier.

In Figure 3 we plot the October 28 count spectra between 500 and 520 keV that was accumulated from 11:06 to 11:16 UT, when the annihilation line was broad, and from 11:18 to 11:30 UT, when it was narrow. The spectra were obtained by subtracting the best-fitting bremsstrahlung and nuclear contributions. The ~1 keV line width late in the flare is the narrowest measured by the *RHESSI* spectrometer in space. The curves are the best fits to the data, using a Gaussian line and positronium continuum. As shown in the third panel of Figure 1, the flux in this continuum fell rapidly within the first 4 minutes. The time-averaged flux in the continuum during the November 2 flare was consistent with zero. In Figure 4 we plot an expanded view of the background-corrected count spectrum that reveals the continuum as a step function below the annihilation line during the first 4 minutes of the October 28 *RHESSI* observation. The solid line is a fit using the expected positronium-continuum spectrum. Another significant component in the spectrum is the ^{7}Li-^{7}Be line complex formed in the fusion of flare-accelerated α particles with ambient ^{4}He (Kozlovsky & Ramaty 1974; Share et al. 2003b). We fit this complex (*dotted line*) with a model, assuming a downward isotropic distribution of accelerated particles at the heliocentric angle of 30°. A fully isotropic particle distribution produces a broader line complex that reduces the measured flux in the positronium continuum. Since both angular distributions provide acceptable fits to these and earlier *RHESSI* and *SMM* α-^{4}He line data (Share et al. 2003b), we averaged the derived positronium fluxes and increased their uncertainties.

3. DISCUSSION

We summarize the *RHESSI* annihilation line and continuum observations for the 2002 July 23, 2003 October 28, and 2003 November 2 flares in Figure 5, where we plot the inferred $3\gamma/2\gamma$ ratios and FWHM Gaussian line widths. The scale at the top of the figure gives the temperature, assuming the line is thermally broadened (Crannell et al. 1976), and the dashed curves indicate the calculated $3\gamma/2\gamma$ ratio as a function of density (H cm^{-3}) for fully ionized H. The July 23 average width was the broadest of the three flares. Because its measured $3\gamma/2\gamma$ ratio was highly uncertain, we were not able to exclude the possibility

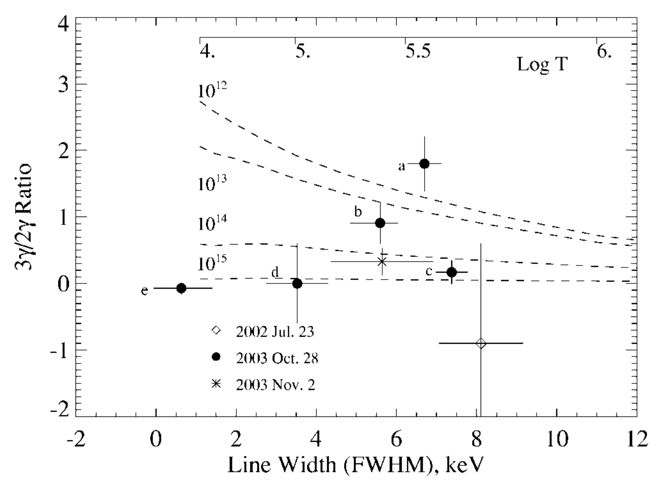

FIG. 5.—*RHESSI* measurements of the $3\gamma/2\gamma$ ratio vs. 511 keV line width (statistical and instrumental uncertainties added in quadrature) for three flares. Time intervals for the October 28 flare measurements are: (a) 11:06:20–11:08:20, (b) 11:08:20–11:10:20, (c) 11:10:20–11:16:20, (d) 11:16:20–11:18:20, and (e) 11:18:20–11:30:20 UT. The November 2 measurement was made between 17:16 and 17:26 UT, when the line was broad. The data point when the line was narrow is consistent with point e. The July 23 measurement was integrated over the entire flare. The temperature scale and curves showing the calculated $3\gamma/2\gamma$ ratio vs. 511 keV line width for different densities are for a fully ionized medium. Measured $3\gamma/2\gamma$ ratios only provide lower limits on densities, because of possible contributions from Compton scattering (see text).

that the broad line originated in positronium formation by charge exchange in flight at ~6000 K in a quiet atmosphere (Share et al. 2003a). With the improved statistics of the new flare observations, we find that the measured $3\gamma/2\gamma$ ratios are inconsistent with the value of 3.7 expected for the quiet atmosphere. We therefore conclude that the broad 511 keV line mostly originates from positrons annihilating at temperatures above 10^5 K and densities $\geq 10^{13}$ H cm^{-3}. This interpretation provides challenges for our current understanding of the solar atmosphere. However, there is earlier evidence for such high-density and high-temperature environments in flares. Doschek et al. (1977) used *Skylab* UV observations to identify compact 0″.1–1″.0 regions at temperatures of $\sim 1.3 \times 10^5$ K and electron densities $\geq 10^{13}$ cm^{-3} that appeared during a 1 minute interval in the 1973 June 15 flare.

Figures 1 and 5 reveal the striking evolution in the 511 keV line width and continuum-to-line ratio in the October 28 flare. During the first 10 minutes of the *RHESSI* observation, when the width was relatively constant, there was a marked reduction in the $3\gamma/2\gamma$ ratio. The high ratio measured between 11:06 and 11:10 UT just after the *CORONAS-F* detection of above 60 MeV photons (Panasyuk et al. 2004), which is likely from π^0 decay, is probably due to annihilation of the related π^+-decay positrons with energies of tens of MeV. Notably, the only two flares with significant (>3 σ) positronium continuum observed by *SMM* (Share et al. 2003a) also produced pions (Vestrand et al. 1999). Upward-moving positrons with these energies can escape from the high-density ($\sim 10^{15}$ H cm^{-3}) regions where they were produced and can annihilate at lower densities from the triplet state, producing a high $3\gamma/2\gamma$ ratio. However, there is another possible source for the continuum. Downward-moving high-energy positrons from π^+ decay and from pair production following π^0 decay can reach high column depths (≥ 5 g cm^{-2}) and annihilate. Compton scattering of these 511 keV line photons produces a spectrum that we cannot distinguish from the positronium continuum (Forrest 1982). Because of this possible contribution, the measured $3\gamma/2\gamma$ ratios early in the October 28 flare (*data points a and b*) only provide lower limits on the density in the annihilation region.

The broad annihilation line observed after 11:10 UT on October 28 (Fig. 5, *data point c*) was mostly produced by positrons, having a mean energy of ~0.5 MeV, and from radioactive nuclei with half-lives ≥ 100 s. Because these low-energy positrons cannot escape from the region where they are produced ($\sim 10^{14}$–10^{15} H cm^{-3}; Hua et al. 1989), they must have annihilated in a high-temperature region at such densities. This is consistent with the observed low $3\gamma/2\gamma$ ratio. The narrowing of the 511 keV line width to ~1 keV in 2 minutes at 11:16 UT suggests a rapid reduction in the temperature where the positrons annihilated. This change was not correlated with the impact rate of high-energy electrons and ions on the solar atmosphere reflected in the bremsstrahlung continuum and nuclear deexcitation line fluxes (Fig. 1). There is evidence for a similar narrowing in the November 2 flare (Fig. 2).

Our interpretation that the broad 511 keV line observed in the three *RHESSI* flares originated in a $\sim 10^{13}$–10^{15} H cm^{-3} medium at more than 10^5 K needs to be confirmed by detailed calculations of the production, transport, and annihilation of the positrons. Assuming no losses, we estimate that $\sim 10^{29}$ ergs would be required to heat a volume of 10^{24} cm^3 of H at a density of 10^{15} H cm^{-3} to a temperature of 4.0×10^5 K. Because radiative cooling occurs on below 1 s timescales at these temperatures and densities (Raymond et al. 1976), a continuous input of energy into the region appears to be required. The more than 10^{32} ergs in accelerated ions estimated from γ-ray line studies could be the source, but the changes in line width and rate of ion energy deposition do not appear to be correlated. It is possible that the accelerated-particle impacts moved from a hot to a cold environment, but the long half-lives of the β^+-unstable nuclei would not allow for the observed rapid narrowing of the 511 keV line. This suggests that there is some other heating source such as low-energy ions that do not produce γ-rays or chromospheric reconnection.

Our calculations indicate that the narrow ~1 keV wide annihilation line and low $3\gamma/2\gamma$ ratio (99% upper limit 0.2) observed late in the October 28 flare are consistent with annihilation in ionized H at $\geq 10^{15}$ H cm^{-3} and below 10^4 K. Ionized material at these densities is also required to explain the excess in low first ionization potential (FIP) elements derived from γ-ray line studies of these and earlier flares (Ramaty et al. 1995). Energetic particles (e.g., Zharkova & Kobylinsky 1993) and backwarming by enhanced UV continuum emission originating in the upper chromosphere (Metcalf et al. 1990) may be the source of ionization, which can last for tens of seconds because of the long relaxation timescales at these densities (Carlsson & Stein 2002).

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